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Sensors and Techniques for Structural Monitoring

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Abstract

This paper summarizes measurement requirements for the monitoring of engineering structures and describes new sensor/system configurations that are finding useful application in field studies. To meet the special needs of structural monitoring, specific areas in need of additional research and development are identified.

Introduction

Data recovered from instrumented structures can be of considerable value in understanding structural behavior under both normal and extreme loading conditions. While structural monitoring may be thought of as a short-term undertaking to obtain the required data, several years of continuous monitoring may be required to capture rare or extreme events, or to quantify phenomena such as creep, settlement or structural degradation. Recent developments in sensor technology and improvements in data acquisition systems have created new opportunities for obtaining reliable field measurements of structural behavior.

To assess the potential of these new technologies and measurement techniques for structural engineering applications, a two-day workshop was held at the National Institute of Standards and Technology (NIST) in 1989. The state-of-the-art and needs for additional research and development were addressed in a series of theme papers (Abdel-Ghaffar and Masri 1989; Crist 1989; Dalgliesh 1989; Reinhold 1989). The major findings and recommendations

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resulting from this workshop, along with certain observations of the author, are summarized in this paper.

Measurement Requirements for Structural Applications

Measurement requirements in the general areas of ground motion, wind speed, wind pressure, structural frame response, component response, and creep or settlement are summarized in Table 1. The indicated bandwidth, range, sensitivity and resolution are based on the collective judgement of experts in the field and on selected field measurement programs that have been carried out on full-scale structures.

Table 1. Measurement Requirements for Structural Engineering Applications.

GROUND MOTION:	
Bandwidth 0.01 to 50 Hz	Range = 1 x 10^{-4} to 2 g
Sensitivity = 1 x 10^{-4} g	Resolution = 1 in 20,000
WIND SPEED:	
Bandwidth = 2.8 x 10^{-4} to 20 Hz	Range = 1 to 80 m/s
Sensitivity = 0.05 m/s	Resolution = 1 in 1,500
WIND PRESSURE:	
Bandwidth = 8.3 x 10^{-4} to 30 Hz	Range = 5 Pa to 6 kPa
Sensitivity = 5 Pa	Resolution = 1 in 1,300
FRAME RESPONSE:	
Bandwidth = 0.01 to 20 Hz	Range = 1 x 10^{-4} to 3 g
Sensitivity = 1 x 10^{-4} g	Resolution = 1 in 30,000
COMPONENT RESPONSE:	
Bandwidth = 0.1 to 200 Hz	Range = 0.005 to 15 g
Sensitivity = 0.001 g	Resolution = 1 in 15,000
CREEP OR SETTLEMENT:	
Duration = 10 yrs or more	Range = 0.1 to 150 mm
Sensitivity = 0.1 mm	Resolution = 1 in 600

Table 2 presents a summary of sensors and technologies that have been applied to the measurement of position, displacement, velocity, pressure and/or force in structural engineering applications. This list is by no means exhaustive. For example, strain, capacitance and inductance devices, as well as fiber optics technologies, have been applied to most of the measurement areas listed.

Table 2. Devices and Technologies for Measuring Position, Displacement, Velocity, Acceleration, Pressure and Force.

POSITION/DISPLACEMENT:

- Dial gages
- Potentiometers
- LVDTs
- Optical devices
- Ultrasonic devices
- Laser
- Radar

VELOCITY:

- Anemometers
  - Cup
  - Propeller
  - Heat transfer
  - Sonic
  - Laser
  - Vortex shedding
  - Fluid drag
- Geophones
- String potentiometer

ACCELERATION:

- Force/displacement devices
- Servo systems
- Piezoelectric devices
- Micro-machined chips

PRESSURE:

- Manometers
- Diaphragm devices
- Bourdon tubes
- Piezoelectric

FORCE:

- Dynamometers
- Force balance devices
- Load cells

Sensor/System Configurations

The traditional approach to sensing and data acquisition has been to connect a sensor array to a central data acquisition system through signal cables that are used to transmit information in one direction only. Using this approach, signal conditioning, A to D conversion, sensor compensation, recording and limited data analysis are carried out at the central data system. With the advent of more sophisticated "smart" sensors, it has become possible to perform some of these operations within the sensor itself, e.g., environmental compensation and self-calibration. State-of-the-art sensor/acquisition systems now allow two-way communication so that additional functions such as gain ranging, selective active filtering, A to D conversion, linearization, self-diagnostics, and even some data processing can be carried out at the sensor. In fact, it is now possible to configure and house sophisticated sensor/acquisition systems in small, self-contained packages that can operate in either a standby or active mode for periods of several months. These systems are ideal for long-term observations or for capturing rare and unpredictable events.

Areas in Need of Additional Research and Development

There are several areas of sensor/measurement technology and application that are in need of additional research and development to meet the special needs of structural monitoring. Some of the more urgent areas of application are listed below.

SENSOR TECHNOLOGY:

- Sensors suitable for measuring angular displacements (rotations) in structures. These sensors should have the following characteristics: Range = ± 3 degrees. Sensitivity = 1 volt/degree minimum. Bandwidth = DC to 10 Hz.
- Displacement/deflection meters for measuring relative movements of structural members.
- Development of silicon-chip based accelerometers with a sensitivity range of 10^{-4} g to 3 g and frequency ranges of 0.01 to 20 Hz and 0.1 to 200 Hz.
- Development of an auto-ranging micro-barometer with resolution down to 5 Pa for measuring wind-induced mean and fluctuating internal pressures in enclosed buildings.

SEISMIC EFFECTS:

- Sensors for the measurement of long-period ground motions (periods of 3 seconds and longer).
- Innovative instrumentation to measure dynamic shear strain in soil.
- Improved instrumentation for the long-term measurement of dynamic pressures in soils.

Appendix I. References

Abdel-Ghaffar, A.M. and Masri, S.F. (1989). "Seismic Sensors and Measurement Techniques for Assessing Structural Performance." Proceedings, International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance, NISTIR 89-4153, National Institute of Standards and Technology, Gaithersburg, MD, pp 3-14.

Crist, R.A. (1989). "Effects Due to Occupancy, Traffic, Snow & Other Loads." Proceedings, International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance, NISTIR 89-4153, National Institute of Standards and Technology, Gaithersburg, MD, pp 21-26.

Dalgliesh, W.A. (1989). "Wind Effects." Proceedings, International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance, NISTIR 89-4153, National Institute of Standards and Technology, Gaithersburg, MD, pp 15-20.

Reinhold, T.A. (1989). "Sensor Technology." Proceedings, International Workshop on Sensors and Measurement Techniques for Assessing Structural Performance, NISTIR 89-4153, National Institute of Standards and Technology, Gaithersburg, MD, pp 27-32.

- Guidelines for the optimum configuration of sensor arrays.
- Common measuring systems for wind and seismic effects.

WIND EFFECTS:

- Development of portable and rapid-deployment units for the measurement of wind speed and direction.
- Remote sensing devices for the measurement of wind speed and direction around buildings and other structures.
- Absolute pressure transducer and steady reference pressure probe.
- Instrumentation and measurement methods and for the reliable determination of internal pressures.

OCCUPANCY, TRAFFIC, SNOW & OTHER LOADS:

- Non-destructive measurement technique to verify the presence of corrosion and to quantify the rate of corrosion in embedded steel elements.
- Techniques for the real-time measurement of live loads on bridges and buildings, and the monitoring of loads during construction.
- Instrumentation and techniques for measuring roof snow and ice loads.

Conclusions

New materials and technologies are having a dramatic impact on the reliability and versatility of sensors and measurement systems. Self-diagnostics and "smart" sensors are making possible more reliable and more efficient field measurements. Low-cost microprocessors, combined with non-volatile memory systems, are making it possible to collect, process and store data in either continuous or intermittent modes for periods of up to several years. To make the best possible use of these new technologies, it is necessary to define the sensor and system requirements that are unique to structural engineering applications.